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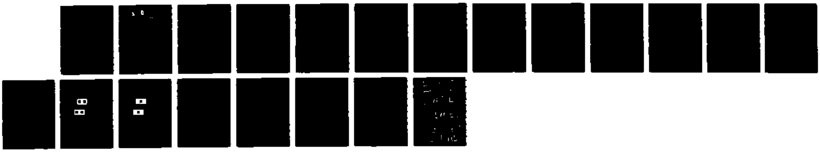

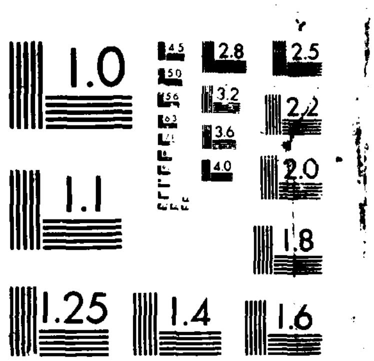

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REPORT DOCUMENTATION PAGE

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1b. RESTRICTIVE MARKINGS	
2b. DECLASSIFICATION / DOWNGRADING SCHEDULE	3. DISTRIBUTION / AVAILABILITY OF REPORT Approved for public release; distribution unlimited.
4. PERFORMING ORGANIZATION REPORT NUMBER(S)	5. MONITORING ORGANIZATION REPORT NUMBER(S) AFOSR-TR- 88-0547
6a. NAME OF PERFORMING ORGANIZATION LAWRENCE E. AREND EYE RESEARCH INSTITUTE of Retina Found. 6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION AIR FORCE OFFICE OF SCIENTIFIC RESEARCH
6c. ADDRESS (City, State, and ZIP Code) BOSTON, MA 02114	7b. ADDRESS (City, State, and ZIP Code) BUILDING 410 BOLLING AFB DC 20332
8a. NAME OF FUNDING/SPONSORING ORGANIZATION AFOSR 8b. OFFICE SYMBOL (If applicable) NL	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER AFOSR-86-0128
8c. ADDRESS (City, State, and ZIP Code) Bldg. 410 Bolling AFB, DC 20332-6448	10. SOURCE OF FUNDING NUMBERS PROGRAM ELEMENT NO. 61102F PROJECT NO. 2313 TASK NO. A5 WORK UNIT ACCESSION NO.

DTIC ELECTE MAY 2 0 1988 S D

11. TITLE (Include Security Classification)
Eye Movements + Spatial Pattern Vision

12. PERSONAL AUTHOR(S) AREND, LAWRENCE E.

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
ANNUAL	FROM 3/1/87 TO 2/29/88	88 MARCH 31	17

16. SUPPLEMENTARY NOTATION

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	SPATIAL PATTERN VISION, VISUAL ILLUSIONS, COLOR CONSTANCY, COLOR VISION

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

Models of lightness and color perception must take account of human color constancy, a tendency for apparent surface color to be relatively independent of the color and intensity of the illuminating light source.

Observers matched the lightnesses and brightnesses of regions in simple and complex achromatic spatial patterns. The data showed that the observers' knowledge of the surface reflectances (revealed by lightness matches) was unaffected by changing brightness of the same surfaces (revealed by brightness matches).

In the analogous chromatic experiments, observers matched the hue and saturation of patches or the patches' apparent surface colors. The observers' knowledge of the surface colors was not as reliable as in the achromatic case. Patches' hues and saturations matched when their chromaticities were approximately the same. Shifts of hue attributable to simultaneous color contrast were in the correct direction but too small to produce hue constancy.

20. DISTRIBUTION / AVAILABILITY OF ABSTRACT ☐ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION
22a. NAME OF RESPONSIBLE INDIVIDUAL Dr. John Tangney	22b. TELEPHONE (Include Area Code) (202)767-5021 — 22c. OFFICE SYMBOL NL

DD FORM 1473, 84 MAR — 83 APR edition may be used until exhausted. All other editions are obsolete.

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AFOSR-TR- 88-0547

ANNUAL TECHNICAL REPORT
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Lawrence E. Arend
Principal Investigator

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I. OBJECTIVES

A. Model Development

The basic model was able to calculate crude lightness predictions for consistent achromatic patterns and segmentable, inconsistent patterns. We proposed to develop and evaluate algorithms for lightness predictions from nonsegmentable inconsistent patterns.

B. Lightness and Color Constancy

We proposed to extend our first experiments on simultaneous lightness and color constancy in complex spatial patterns to consider several additional variables. Interactions in the previous year with researchers at Stanford and elsewhere made it clear that understanding of simultaneous mechanisms will require careful study of the relationship between temporal adaptation constancy mechanisms and simultaneous mechanisms.

II. STATUS OF RESEARCH EFFORT

A. Model Development

Our reports of our work on color and lightness constancy were received with great enthusiasm by the vision research community, with the result that most of our time and energy was consumed in presentation of those experimental results and extension of the constancy work. As a result there was disappointingly little time for further development of the spatial integration model. Nevertheless, we did make some progress toward implementing a version of Blake's integration algorithm for patterns which are neither consistent nor segmentable. Blake's model is analytically identical to ours in many respects, the most important difference being that Blake's model inflexibly applies the "gradient manipulation" type of integration algorithm to all patterns, making poor predictions of the appearance of segmentable, inconsistent patterns, e.g., a shallow linear sawtooth with a dark surround (fig. 1). Blake supplied us with his code, and we have completed the process of converting it to run in our software environment (conversion from UNIX and C to VMS and FORTRAN). The effort was much greater than anticipated and a number of modifications are still required, but we did succeed in getting the model to generate

illusory gradient patterns similar to those reported by our human observers, using the circumferential sawtooth and induced sawtooth patterns we have used in our human experimentation. The main remaining barriers to rapid advances in this part of the model work are, on the theoretical side, the very slow convergence of the algorithm and, on the experimental side, the absence of good methods of psychophysically measuring gradual spatial changes of brightness. We hope to attack both these problems in the coming year.

We also interacted extensively with the Grossberg group at Boston University concerning their attempts to account for essentially the same family of shallow-gradient illusions that our model was designed to explain. Unlike Blake's model theirs is structurally very different from ours, using a complex form of local filling-in rather than global integration. It is now clear that their model is unable to account for our observation that our radial sawtooth illusions (modifications of the Craik-OBrien-Cornsweet illusion).are essentially unaffected by reversal of the contrast of the surround luminance. Their model's success in predicting the illusory appearance applies only to one or the other surround luminance, depending on the direction of the sawtooth. Our observations are only qualitative so far, but the phenomena are so robust that there is little doubt that our previously successful brightness matching technique will produce the necessary quantitative evidence. We hope to find time to run this experiment in the coming year.

On a more cooperative level, we have had promising discussions with Dr. Mingolla from Dr. Grossberg's group regarding collaborations on projects to investigate methods for matching gradual changes of brightness and measurement of surface colors in apparently three dimensional patterns. At this point it is not clear when either of us will be able to free the time for the collaboration, but the discussions themselves have been useful.

B. Lightness and Color Constancy

We made substantial progress on both lightness and color constancy during the past year. In the case of lightness constancy the progress was mostly in the form of improved theoretical understanding, greatly stimulated by participation in a symposium at an August meeting in Trieste, Italy. The symposium participants were largely unaware of each others work prior to the meeting and were all pleasantly surprised to discover that we shared a common

approach to the lightness constancy problem, but with sufficient differences to produce very productive discussions and arguments. The ten hours of conversation in Italy has led to extensive correspondence among Drs. Paul Whittle (Cambridge, GB), Alan Gilchrist (Rutgers) and myself. In the case of Dr. Gilchrist, our several subsequent visits to each others labs have helped shape substantial changes in my understanding of the role of my edge-integration model in surface color perception. A small part of these changes was included in my Annapolis and BU talks (see list below) and more will be included in the published proceedings of the BU meeting, now in preparation. I still see the model as describing important properties of the differentiation and integration processes involved in surface color computations. It is also now becoming clearer to me how the model can be extended beyond the current restricted set of viewing conditions toward the kinds of patterns used in our constancy experiments.

The interactions with Dr. Whittle have helped clarify for me another direction in which the model needs to be expanded. It may be possible in the next few years to replace the mathematically convenient approximations in the compressive and threshold stages of the model with more sophisticated approximations to the adaptation behavior of the visual system, linking our model to his work on edge ratios and adaptation.

We ran experiments significantly extending our first chromatic constancy experiments (J. Opt. Soc. Amer. A, 1986). All of the original experiments concerned simultaneous constancy, i.e., scenes with multiple illuminants, viewed under chromatic adaptation to one of the illuminants. In the extensions we ran essential control experiments and began consideration of the relation between simultaneous constancy mechanisms and chromatic adaptation mechanisms.

In the original experiments the subjects viewed a continuously presented scene containing two identical arrays of colored papers under different illuminants. We relied on voluntary eye movements to maintain constant chromatic stimulation over integration times on the order of tens of seconds in order to avoid extensive chromatic adaptation to the color of the test illuminant. To assess the adequacy of this strategy we matched hues and saturations in a paradigm in which the Mondrian display was exposed for 1 s, in alternation with 5 s exposure to a uniform field of the 6500 K adapting light (Fig. 1). As predicted, the data did not differ significantly from the original experiments. Hue and saturation

matches differed from chromaticity matches in the correct direction for hue and saturation constancy, but by far too little.

We also considered the possibility that significant simultaneous hue shifts might occur in scenes containing a single illuminant. In all the earlier experiments the stimuli included both the standard and test illuminants, i.e., there was a spatial illumination edge in the scene. We made hue and saturation matches in a paradigm with the test and standard Mondrians presented in separate 1s time intervals, separated by 1s of adapting field. As in the previous experiments the observed simultaneous hue and saturation shifts were much smaller than required for constancy of hue and saturation. The data were slightly ambiguous, however, with respect to the size of the shifts relative to the previous conditions. Inspection of the plots of the data in u'v' chromaticity space suggests that the shifts may be slightly larger in the single illuminant scenes. We are now attempting to solve the difficult problem of finding a univariate statistic expressing the degree of shift toward constancy. This problem has plagued our work from the beginning. There is no widely accepted index of chromatic constancy analogous to the Thouless ratio in lightness and brightness constancy. Among the several reasons are the lack of a universally accepted set of chromatic dimensions for comparison and perceptual nonuniformity of the color spaces that have become widely accepted. We are currently evaluating the index

$$C = 1 - d(m,t)/d(s,t),$$

where d(m,t) is the Euclidean distance in u'v' between the subject's mean match and the chromaticity required for constancy and d(s,t) is the distance between the chromaticity of the standard stimulus patch and the chromaticity required for constancy. This index is therefore zero when there is a chromaticity match of test and standard patches (no constancy) and one when the subject sets the test patch to the chromaticity required for perfect constancy. This index has the advantage of directness and simplicity, but it is not likely to fully satisfy color theorists due to the residual perceptual nonuniformities of u'v' color space. If the statistic proves useful we will use it until a better method is developed, by us or by others. The statistic should confirm all of the conclusions we have drawn to date and it should allow slightly more detailed analysis of the data.

We also began collecting data on adaptive hue shifts, for comparison with our simultaneous data. A common problem in evaluation of color percepts under different chromatic adaptations

is provision of a stable yardstick, i.e., a standard stimulus with constant appearance. This has most commonly been done by placing a standard patch of constant chromaticity in one eye, adapted to the standard illuminant, and a test patch in the other eye, adapted to the experimental illuminant. This method suffers from the possibility of contamination due to interaction between the adaptive states of the two eyes (there is recent experimental evidence to justify this concern). We have chosen to avoid this problem by presenting only the test stimulus, with the subject adapted to the experimental illuminant. The constant yardstick is achieved by asking the subject to always adjust the red test patch to a unique red of half-maximum saturation, i.e., to provide an internal standard stimulus. Corresponding adjustments were made for unique green, yellow, and blue, and a neutral gray adjustment. Three adapting illuminants were used, 4000 K, 6500 K, and 10000 K. The temporal sequence of the experiment is shown in Fig. 2. Pilot results are shown in Fig. 3. The three minute adaptation to the test illuminant resulted in much larger shifts of hue than we observed in the simultaneous constancy experiments, comparable to the shifts in our apparent surface color ('paper') matches. The data, in conjunction with our simultaneous constancy data, show that the visual system has two quite different color constancy strategies. In slightly overly simple terms, slow *shifts of illumination over the entire visual field result in* normalization of hues, i.e., there is a tendency for a surface to produce approximately the same hue at complete adaptation to the current illuminant. Within scenes the hues of surfaces are primarily determined by the adaptation illuminant. If there are regions in the scene with a different illuminant, the same reflectance will have a different hue, but the observer will nevertheless perceive it to be the same surface color under a different illuminant.

We are currently working on an elaboration of this experiment which will allow us to examine the influence of spatial complexity on adaptive hue shifts.

C. Filling-In Experiments

I returned to SRI in Menlo Park, CA to help complete collaboration with Dr. Piantanida of SRI and Dr. J. Larimer of NASA Ames Research Center, on experiments investigating the influence of illusory "filled-in" colors on sensitivity to superimposed real light. The experiments had proceeded well during my absence, and we wrote a manuscript which has been submitted for publication. The results of the experiments are very clear. The influence of

background light on chromatic flicker sensitivity is not directly attributable to changes in excitation of the surrounding cones, but depends instead on the surround color following the filling-in process. These results have profound implications for further psychophysical study of the organization of opponent color mechanisms. It is not clear how much our lab will be involved in the further development of this work. Our involvement would be welcomed by Drs. Piantanida and Larimer, but the possibilities are limited by time, distance and money. The apparatus required for these experiments is expensive and complicated, and we have no plans currently to develop this capability in our lab.

D. Display Work

In November, while working on a simulation of a scene with low luminance regions, we discovered that our luminance calibrations and gamma correction for higher luminances were seriously inaccurate in this low range. At the same time we were encountering a widespread, undocumented, skepticism among other vision researchers that CRT displays could be luminance-linearized over a range greater than about two log units. Our experience in earlier calibrations had been that our display system was adequately stable over at least three log units (we didn't try to go beyond that). A check of the calibration at higher luminances showed that the machine had drifted enough to make full recalibration desirable (though not required: no previously reported data were in question) so we proceeded to completely revise our gamma corrections, with the intention of extending the controlled luminance range downward as far as possible.

Evaluation of the previous gamma corrections for the three color guns showed that the error was worse for the blue gun than for the other two. This was the first indication in our five year experience with the system that the three color channels might require gamma corrections with different mathematical forms. In fact, though we knew it was inevitable, this was the first indication that aging of our system required serious corrective action. Previously we were in the enviable condition of being able to superimpose the normalized output curves for the three guns with the same power function of the input data, with the advantage that the correction was analytical and uniform over guns.

As a consequence, we must now monitor the gamma correction much more frequently than before, continuing at conservative intervals until we have established the pattern of change, and then

monitoring at the indicated interval. Furthermore, since we now needed different corrections for the three color channels and wanted to extend the range downward into a range where the single exponential analytic correction gave a poor fit, we decided to implement the gamma correction by lookup tables rather than on-the-fly analytic correction. Some of the advantages of the lookup table strategy are that the complexity of the mathematical form of the correction has no consequence for speed, in that the correction algorithm is independent of the nonlinearity of the color channel, and subsequent calibrations will require only that the lookup data table be changed, not the active software. The disadvantage is serious, but manageable. Protection of the lookup data table from human error is more difficult than protection of local analytic correction code. Fortunately this is mostly managed under VMS by establishing a protected directory for display calibration tables. Nevertheless, this is one more aspect of use of CRT monitors in vision research that bears watching.

Our recalibration showed that even the lowest step of our 1024 DAC input range produced reliable changes in the gun luminance. We measured the luminances in a sampling scheme that used the old gamma correction to give approximately linear steps of luminance within each decade of luminance. The measurements were then used as the independent variable and fit with a spline constrained to pass through the data points. The input data values required for the desired luminances are the lookup table entries and were generated from the resulting curve. We then measured the luminances generated by the new algorithm and lookup table and compared them to the nominal luminances. The results were accurate to the limits of our 3 1/2 digit UDT photometer over the entire output range of the display system (Figs. 4,5,6). In the current monitor setup this is a 7000:1 range. This held true over the several days intervening between the initial measurements and the final evaluation. It is unlikely that the monitor is this stable over reasonable periods, but we are confident that a range in excess of 1000:1 can be maintained for the durations required for our experiments. Furthermore, it may be possible to entend the range by adjusting the monitor black level to decrease the luminance corresponding to zero data input. We will try this when the monitor is moved to our new lab in September.

The calibration procedure was particularly slow due to development of the new gamma-correction software, but even with this software the measurements and data manipulation would require about a man-week of research time. This is sufficiently

disruptive to deter frequent recalibrations. To make the process less time-consuming and to reduce human error we have acquired a MacIntosh II system with A/D and D/A capability that will allow us to develop automated calibration procedures. We have only just received the hardware and will begin the software development in the coming two months.

III. PAPERS

Significant time was devoted during this grant period to reporting results of the research project. In addition to appearance of several articles, I gave a number of invited papers.

Arend, L. and Timberlake, G. Reply to Prof. Ditchburn's "Comment on 'What is psychophysically perfect image stabilization? Do perfectly stabilized images always disappear? J. Opt. Soc. Amer. A, **4**, 407-408, 1987.

Arend, L. and Goldstein, R. Lightness models, gradient illusions, and curl. Perception and Psychophysics, **42**, 65-80, 1987.

Arend, L.E. and Goldstein, R. Simultaneous constancy, lightness and brightness. J. Opt. Soc. Amer. A., **4**, 2281-2285, 1987.

Larimer, J., Piantanida, T., Arend, L., and Varner, D. Separation of chrominance and wavelength in color perception. Invest. Ophthal. & Vis. Sci., **28**, March Supple., 93, 1987.

Arend, L.E., Reeves, A., Schirillo,J. and Goldstein, G. Simultaneous color constancy for papers with varying Munsell values. Invest. Ophthal. & Vis. Sci., **28**, March Supple., 213, 1987.

Manuscripts in Preparation

Arend, L.E. Cornsweet illusion without subthreshold gradients.

Arend, L., Reeves, A., Schirillo, J, and Goldstein, R. Influence of luminance diversity on simultaneous color constancy.

Arend, L., Reeves, A. Schirillo, J., and Goldstein, R. Adaptive color constancy in complex patterns.

Larimer, J., Piantanida, T., Arend, L. and Varner, D. Separation of chrominance and wavelength in color perception. Submitted to Science.

IV. PROFESSIONAL PERSONNEL

Arend, Lawrence E., Principal Investigator

Goldstein, Robert, Research Assistant

Reeves, Adam, nonsalaried part-time collaborator

Schirillo, James, nonsalaried part-time collaborator

V. PROFESSIONAL INTERACTIONS

Papers presented:

Larimer, J., Piantanida, T., Arend, L. and Varner, D. "Separation of chrominance and wavelength in color perception," ARVO Annual Meeting, Sarasota, FL, May, 1987.

Arend, L., Reeves, A., Schirillo, J., and Goldstein, R. "Simultaneous color constancy for papers with varying Munsell values," ARVO Annual Meeting, Sarasota, FL, May, 1987.

Arend, L. "Simultaneous color contrast and constancy," Invited Paper, OSA Topical Meeting on Color Appearance, Annapolis, MD, June, 1987.

Arend, L. "Complexities of lightness perception," Invited Paper, Fourth International Conference on Event Perception and Action, Trieste, Italy, August, 1987.

Larimer, J., Piantanida, T., Arend, L. and Varner, D. "Separation of chrominance and wavelength in color perception," OSA Annual Meeting, Rochester,NY, October, 1987.

Arend,L. "Human color constancy," Colloquium, Center for Biological Information Processing, MIT, October, 1987.

Arend,L.."Contrast and constancy," Invited talk, NASA Ames Research Center, CA, November, 1987.

VI. INVENTIONS

There were no patentable inventions during this project period.

Figure Legends

Fig. 1. Timing diagram for flashed two-Mondrian paradigm.

Fig. 2. Timing diagram for adaptation experiment. Test illuminant always corresponded to adaptation and interstimulus illuminant.

Fig. 3. Pilot data from adaptation experiment. Top panel: Subject LA. Bottom panel: Subject AR. Filled symbols: Mean chromaticity settings of unique hues. Open symbols: Chromaticities of test papers in simultaneous experiment (for comparison of distances only). Crosses: von Kries adaptation predictions. Squares: 10000 K illuminant. Circles: 6500 K. Triangles: 4000 K.

Figs. 4,5,6 Lowest three decades of evaluation data, linearization of green gun. Horizontal axis: Nominal normalized green luminance (1.0 = maximum luminance of green gun). Vertical axis: Measured normalized green luminance.

FLASHED PRESENTATION

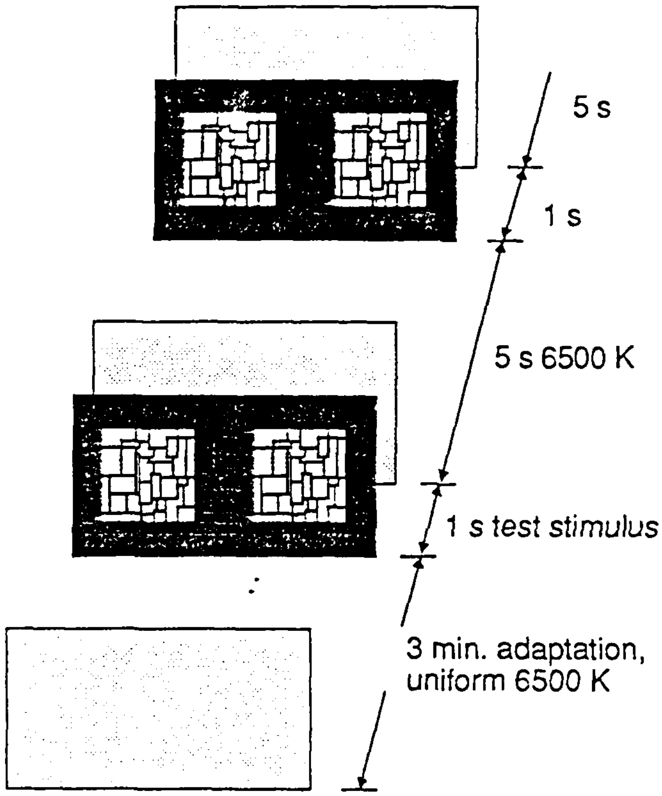


Fig. 1

ADAPTATION

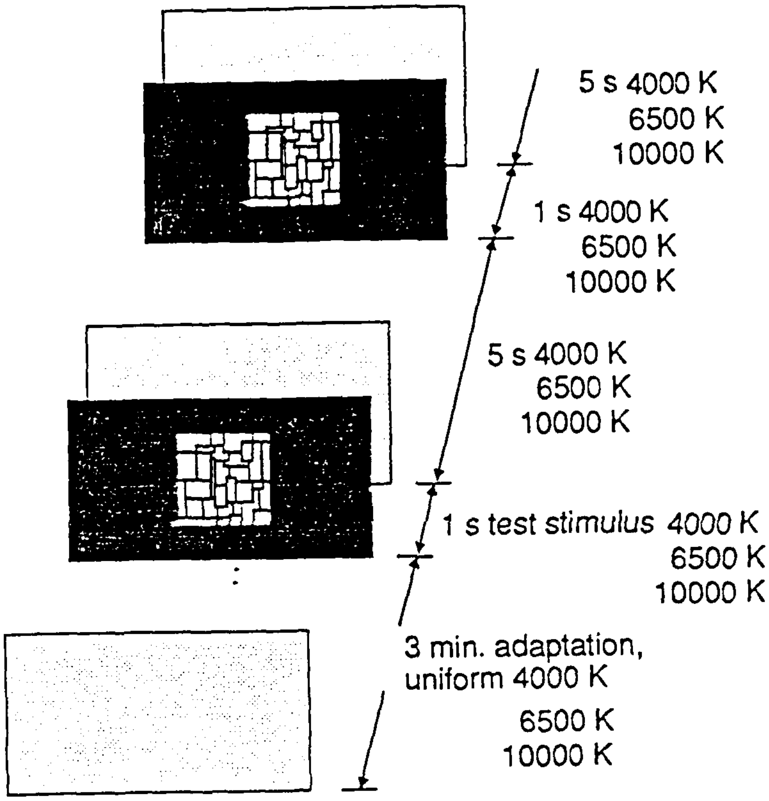
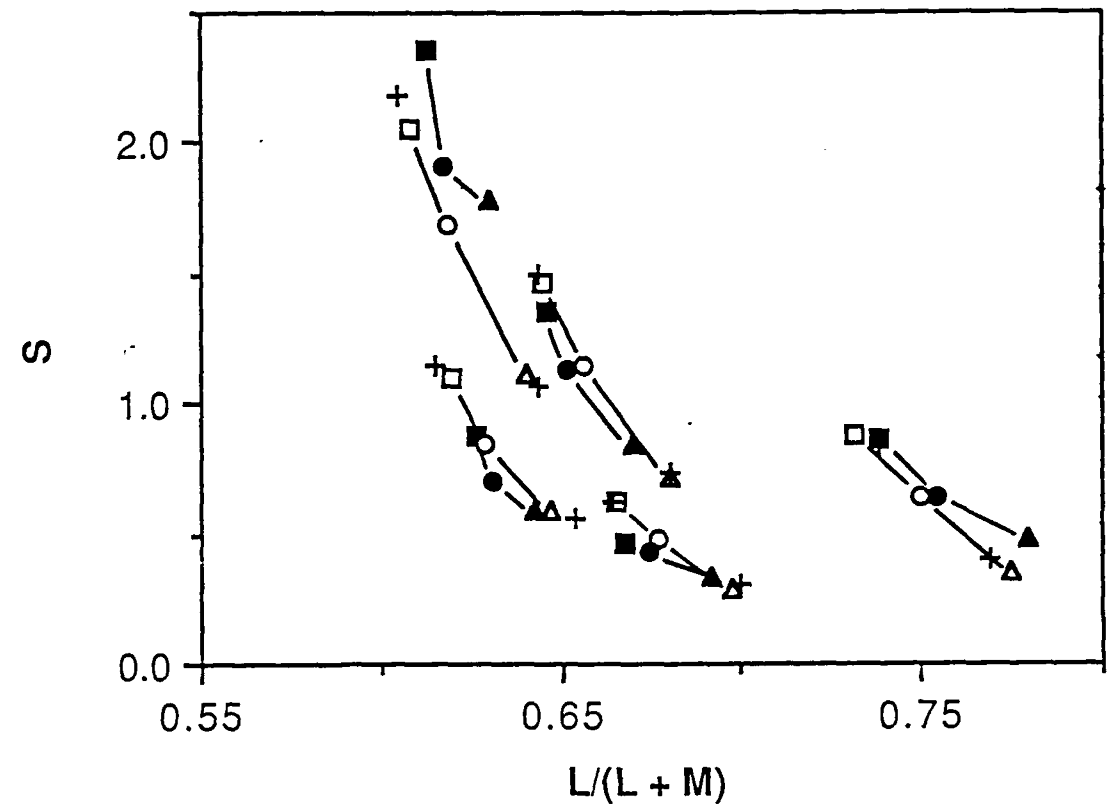


Fig. 2



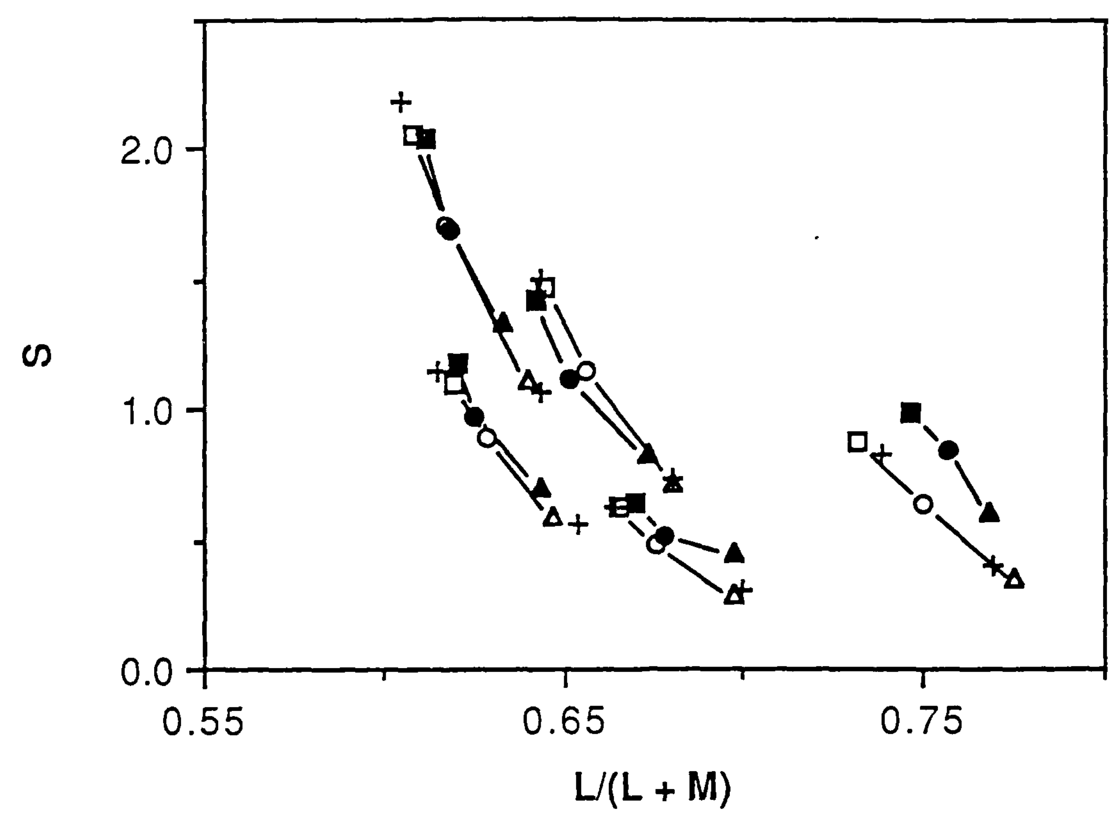
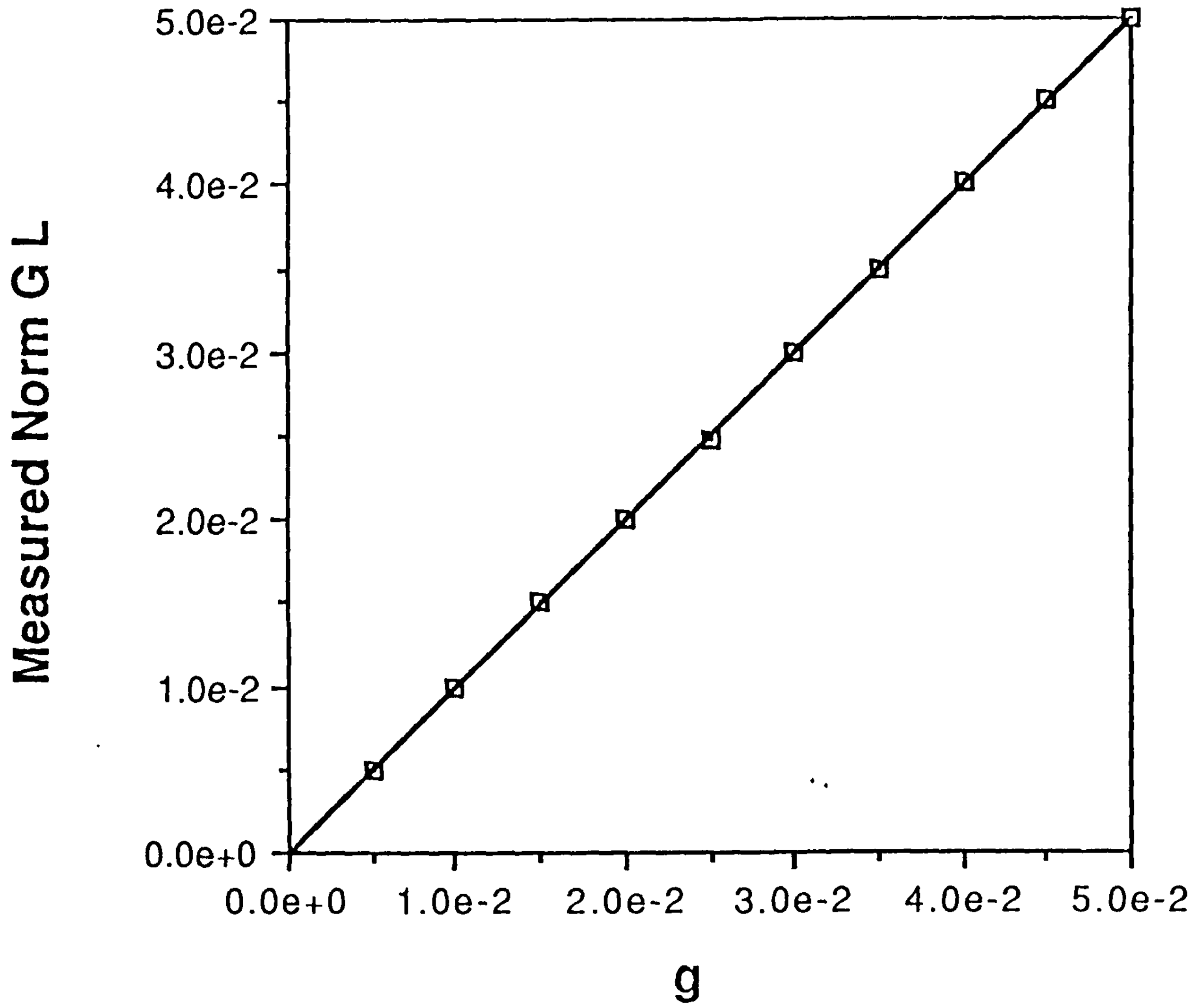


Fig. 3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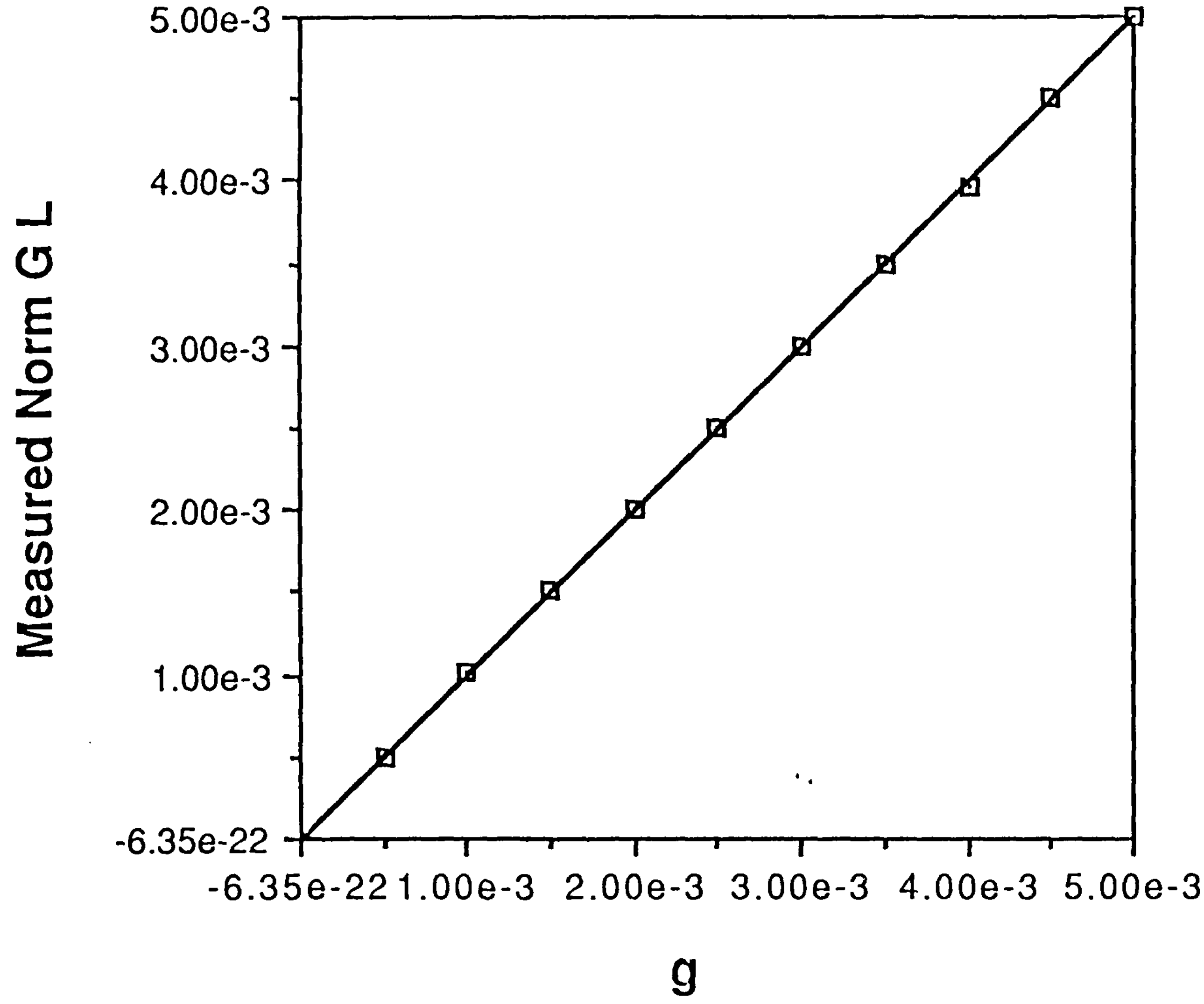

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Fig-5

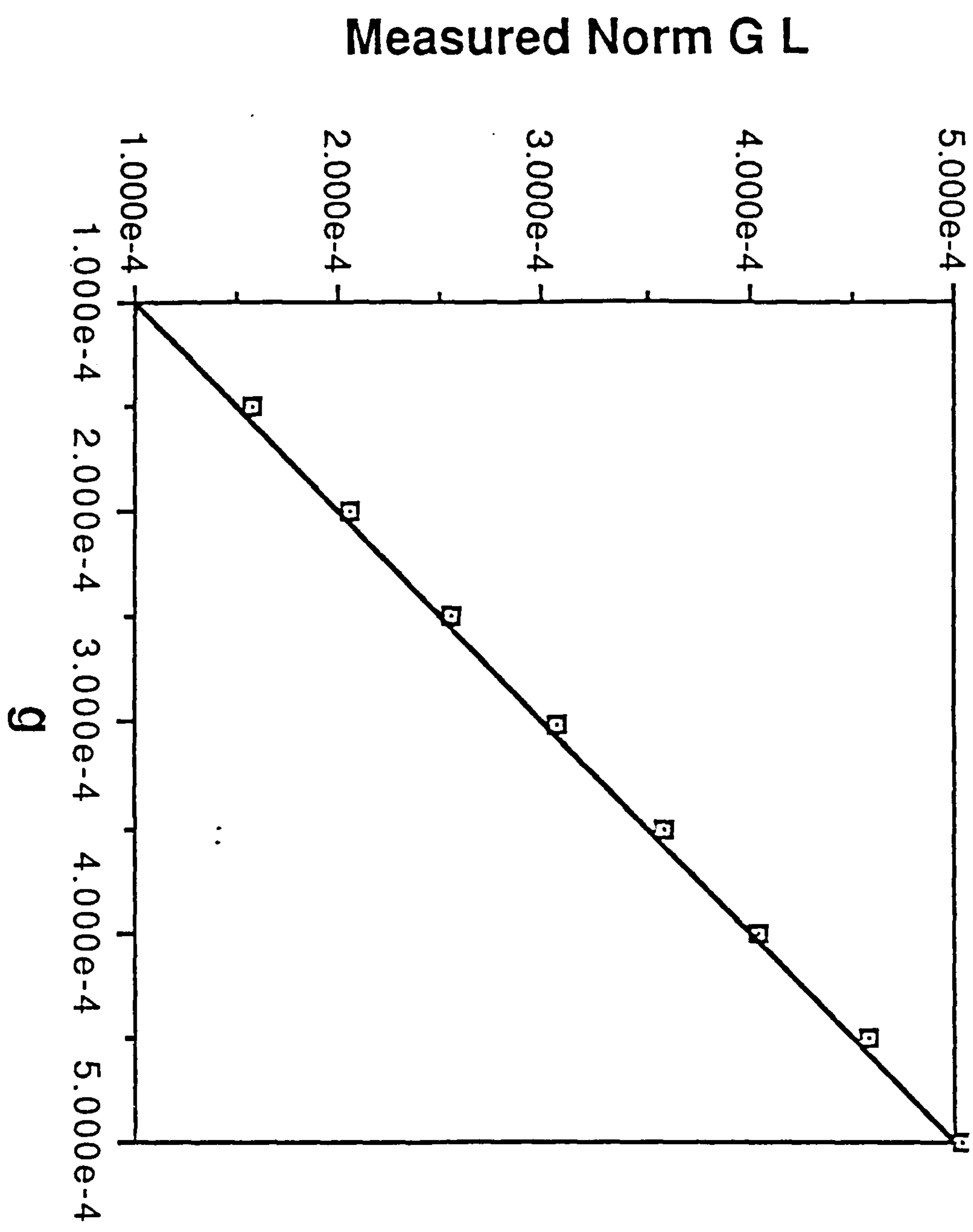

Fig. 6

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